Error sources in SLODAR turbulence profile fitting

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Abstract. This paper discusses some of the main error sources that affect use of the Slope Detection and Ranging (SLODAR) technique to recover atmospheric turbulence profiles from Shack-Hartmann wavefront sensor data. The most significant factor we address here is that of temporal sampling – we examine the effect of poorly-averaged slope correlations due to low wind speeds (or data sets that are insufficiently long) on spatial covariances of wavefront slopes. We discuss how this can affect the observed outer scale of the turbulence. A dual SCIDAR-SLODAR instrument is described that is ideally suited to exploring the impact of these effects and, potentially, correcting them. Some preliminary results from the instrument are presented.

1. Introduction

Slope Detection and Ranging (SLODAR) [1] is an optical turbulence profiling technique that can be implemented using a dedicated instrument or using wavefront slope measurements from a facility adaptive optics system. However, the technique is easier to apply on a small telescope (e.g. 0.5 m [2]) than on a large telescope (e.g. 8 m [3]). This paper describes why, and presents some approaches to ameliorating some of the problems on larger telescopes.

Section 2 gives a brief overview of the main similarities and differences between the Scintillation Detection and Ranging [4] (SCIDAR) and SLODAR techniques. Section 3 explains the factors that contribute to the response of a SLODAR instrument to a layer of turbulence. Section 4 describes a combined instrument that provides simultaneous Scintillation Detection and Ranging (SCIDAR) and SLODAR profiling and section 5 describes an approach to correcting temporal errors in SLODAR profiles using velocity profiles measured using SCIDAR. Section 6 contains the conclusions.

2. Comparison between the SCIDAR and SLODAR techniques

SCIDAR and SLODAR are both 2-star triangulation turbulence profiling techniques. SLODAR uses a Shack-Hartmann wavefront sensor (WFS) to measure local wavefront slopes across the telescope pupil; SCIDAR measures the flux. In both cases the strength and height of turbulence is recovered from peaks in a spatial cross-covariance map. In general, SCIDAR has more resolution elements than SLODAR so yields higher resolution turbulence profiles.

In both techniques, the turbulence profile reconstruction process involves fitting response functions to the cross-covariance peaks. SCIDAR response functions are narrow and localised. SLODAR response functions have wings that extend across much of the covariance map. Examples of both are shown in figure 1.

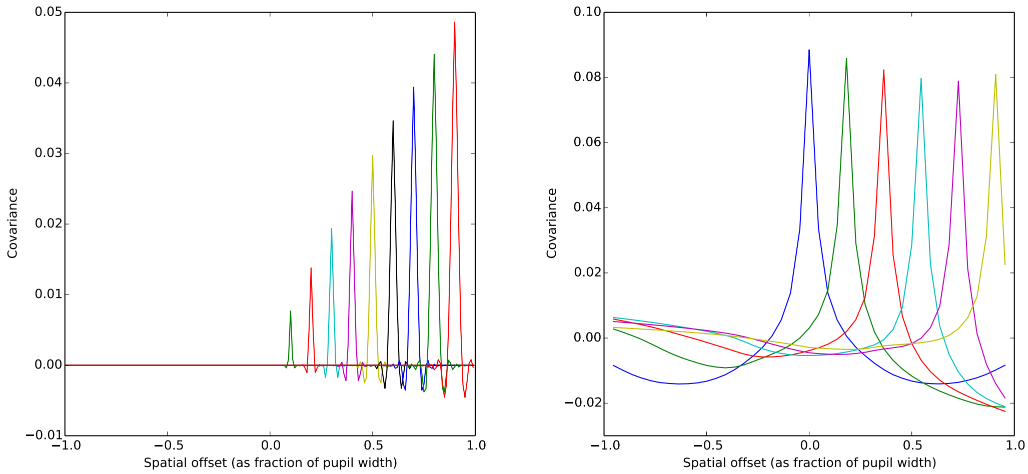

Figure 1. Response functions for (left) SCIDAR and (right) SLODAR. The SLODAR response functions are for wavefront slopes in the longitudinal direction i.e. parallel to the separation direction of the two stars. SLODAR response functions for the transverse direction (not shown) have broader peaks and more extended wings than longitudinal functions.

SLODAR can provide an estimate of the total seeing via a model-fit to the autocovariance (i.e. data from a single star). This is similar to the differential image motion monitor (DIMM) [5], and is independent of the turbulence profile fit. A total seeing estimate for SCIDAR has to come from summing all layers in the turbulence profile, so errors in the profile fit can propagate into the seeing estimate.

3. SLODAR response functions

A SLODAR response function is a model of the cross-covariance measured in response to a single layer of turbulence at a given altitude. Response functions can be generated theoretically [6] or using a Monte Carlo simulation. A response function depends on the following parameters:

(i) Subaperture size.
(ii) Δ, the spatial offset of the peak in the covariance map.
(iii) The height of the turbulence (if scintillation can not be neglected) – this is related to Δ, but also depends on separation of the target stars.
(iv) The shape of the pupil function (assuming we are subtracting tip/tilt to remove telescope shake and tracking errors).
(v) The temporal baseline of the measurement (i.e. the averaging time for the cross-covariance).
(vi) The outer scale of the turbulence.
(vii) The translational velocity of the turbulent layer.

The first five parameters relate to the design of the instrument (or the observing method) and they are generally known. The last two are both properties of the turbulence being measured, are generally unknown and can vary with altitude. Our main concern here is these two parameters and how they interact with parameter (v), the temporal baseline.

In the regime where the covariance is well temporally-averaged (i.e. high wind speed and long temporal baseline) the shape of the response functions is dominated by the outer scale. A larger outer scale leads to broader correlation peaks, as can be seen in Figure 2.

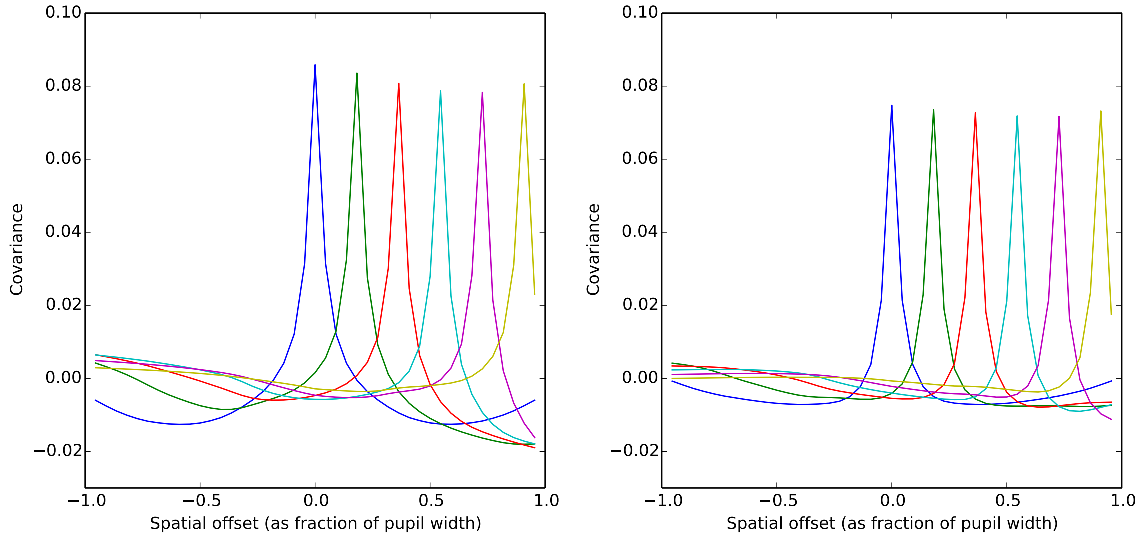

Figure 2. Theoretical SLODAR response functions (longitudinal direction only) for Von Karman turbulence seen by a 2.54 m aperture. Left: $L_0 = 20$ m, right: $L_0 = 5$ m.

The assumption that the covariance response to a layer is well-averaged is not always correct. Covariance measurements of very slowly moving turbulent layers can take a long time to converge, and this effect is exacerbated on larger telescopes (where the pupil crossing time is longer). Larger scale aberrations converge more slowly than smaller scale aberrations so a poorly-converged covariance measurement tends to have a smaller apparent outer scale. This effect can be demonstrated by making outer scale measurements from the same wavefront sensor data using different temporal baselines. An example is shown in figure 3, where the outer scale has been fitted to the same autocovariance data multiple times but with the datasets truncated to different durations.

A simplistic view is that the temporal baseline can be increased until the apparent outer scale is no longer observed to change but this may be unfeasible in practise, especially when the wind speed is particularly low. Firstly, it may be impractical to take sufficiently long datasets e.g. due to other constraints in how the instrument is operated. Secondly, the turbulence profile may vary over shorter timescales than the time required to make a well-averaged covariance measurement.

The example presented here is for the “overall” outer scale i.e. averaged over the whole atmosphere. The outer scale and the turbulence velocity are not necessarily the same at every altitude. The vertical profiles of the outer scale and velocity must be taken into account when generating response functions if they are to fit the measured cross-covariance correctly. Failure to include this effect will lead to errors in the strength and/or height of turbulent layers in the fitted profile.

4. The dual SCIDAR-SLODAR instrument

One approach to investigating temporal effects in SLODAR is to compare with simultaneous SCIDAR data; SCIDAR is not very sensitive to the outer scale and does not require such long datasets to provide well-averaged cross-covariance measurements. The ideal experimental arrangement is to make measurements using both techniques along the same line of sight – for this purpose a dual SCIDAR-SLODAR instrument was built.

The dual SCIDAR-SLODAR instrument was installed by Durham University as a guest

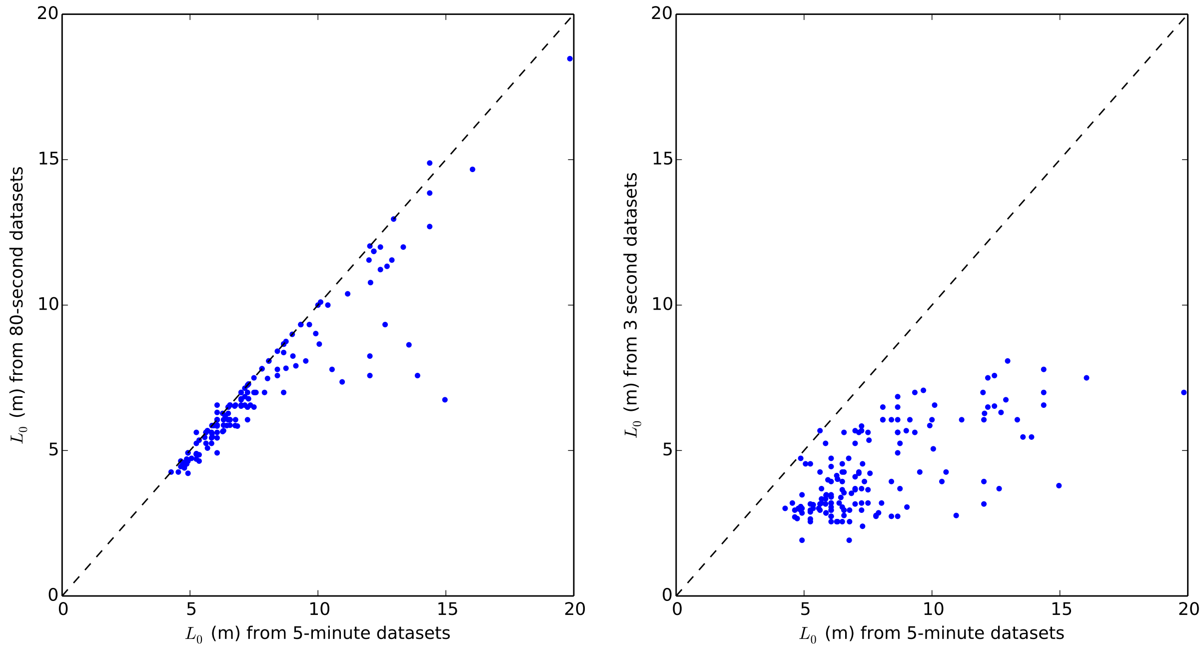

Figure 3. Demonstration of the effect of insufficient temporal averaging on the measured outer scale. Plots show the outer scale measured from a 5-minute data set against the outer scale from the same data cut down to (left) 80 seconds and (right) 3 seconds.

instrument on the 2.54 m Isaac Newton Telescope (INT) on La Palma in July 2014. It is a modification of an existing generalised stereo SCIDAR [7] that has been used to support the CANARY AO demostrator [8]. A dichroic with a cutoff wavelength of 615 nm is used to divert red light into a SLODAR channel. The blue light continues to the SCIDAR optics. The SLODAR channel consists of a single Shack-Hartmann wavefront sensor (WFS) with the two stars interleaved on one Andor "Zyla" SCMOS camera. The WFS has 22×22 subapertures and is suitable for observing pairs of stars with separations of approximately 13 arcseconds or 30 arcseconds.

In addition to measuring the turbulence profile, the SCIDAR instrument measures the wind velocity profile i.e. wind velocity as a function of height. Velocities can only be measured at heights where turbulence is present, but an interpolation routine can be used to estimate the profile at other heights. An example interpolated wind speed profile is shown in figure 4.

5. Wind correction of SLODAR response functions

The wind velocity profile measured from SCIDAR can be used to improve the SLODAR response functions to account for the combination of translation velocity and finite temporal baseline. The response function at each height can be generated (via Monte Carlo simulation) with the correct wind velocity. Two examples of such response functions (for different temporal baselines) are shown in figure 5. For the purpose of this demonstration all layers are assumed to be moving in the same direction but, in order to achieve the best fit possible, the wind direction information for each layer from SCIDAR should also be incorporated. An outer scale of 30 m is assumed here.

Fitting response functions that have been corrected for the wind profile in this manner implies a relatively short temporal baseline could be chosen deliberately in order to allow a turbulence

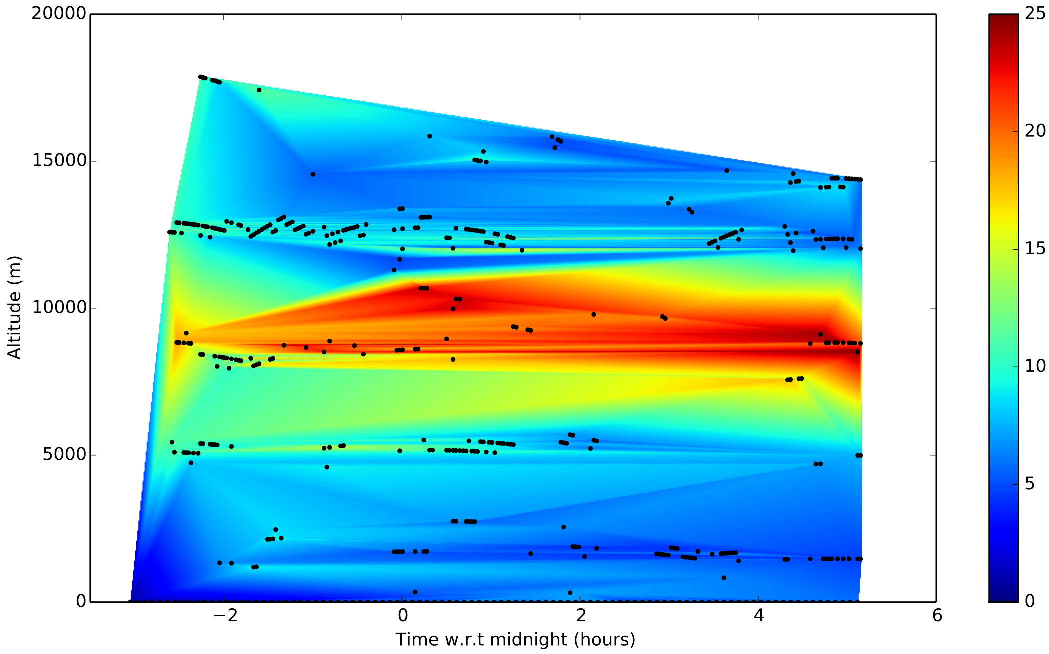

Figure 4. Interpolated wind speed profile (with colour scale in m/s) for the night starting 16 July 2014.

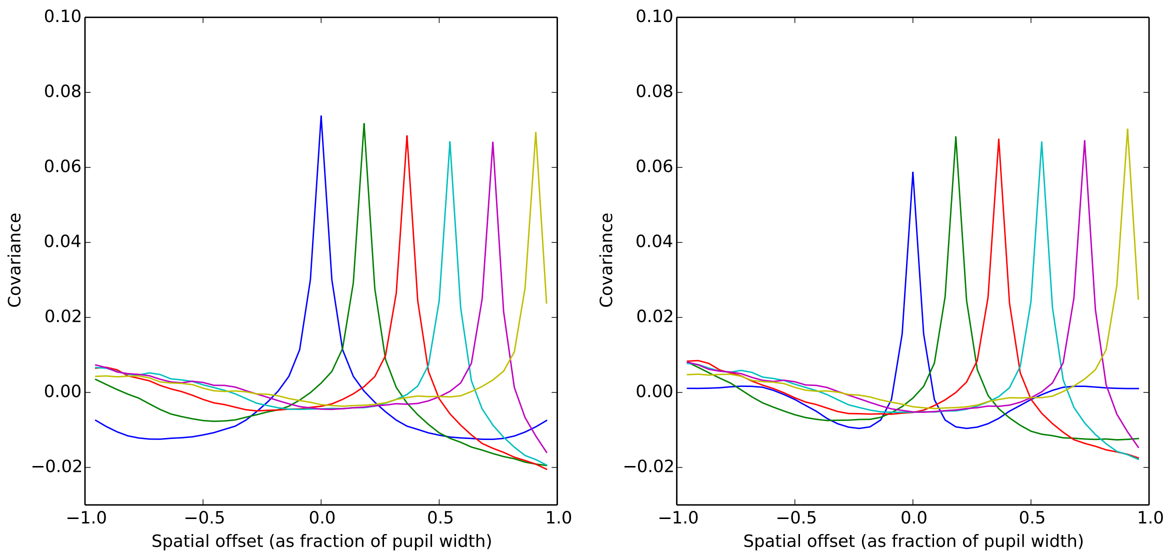

Figure 5. Simulated SLODAR response functions (longitudinal direction only) including correction for the wind speed profile. Left: temporal baseline 10 seconds; right: temporal baseline 1 second. All layers are assumed to be moving in the same direction.

profile to be measured in a shorter amount of time. This correction also suggests more confidence could be placed in outer scale estimates that are obtained via a slope covariance fit.

6. Conclusion
SLODAR turbulence profiles are fitted using response functions that depend on numerous parameters including the outer scale, wind speed and temporal baseline for measurements. Outer scale and temporal effects can vary with altitude and can be difficult to distinguish from one another. This problem tends to be more pronounced on larger telescopes. One approach to solving this problem is to use wind velocity profiles (from SCIDAR or other sources) to compensate for these effects but it remains to be seen whether this allows the outer scale profile to be measured. Further data from the dual SCIDAR-SLODAR instrument will be used to continue this investigation.

Acknowledgments
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